Study of Multi-layer Active Magnetic Regenerators Using Magnetocaloric Materials with First and Second Order Phase Transition

Lei, Tian; Engelbrecht, Kurt; Nielsen, Kaspar Kirstein; Neves Bez, Henrique; Veje, Christian T.; Bahl, Christian

Publication date:
2015

Document Version
Peer reviewed version

Study of Multi-layer Active Magnetic Regenerators Using Magnetocaloric Materials with First and Second Order Phase Transition

Tian Lei[1], Kurt Engelbrecht[1], Kaspar K. Nielsen[1], Henrique Neves Bez[1], Christian T. Veje[2] and Christian R. H. Bahl[1]

[1]Department of Energy Conversion and Storage, Technical University of Denmark, Denmark

[2]Mæsk Mc-Kinney Møller Institute, University of Southern Denmark, Denmark

E-mail:tile@dtu.dk; Mobil: +45-5130-8382

Introduction

To investigate how to layer **Active Magnetic Regenerators (AMR)** using magnetocaloric materials with a **First or Second Order Phase Transition (FOPT or SOPT)**, the following points are studied and discussed based on simulation:

1. Impact of the magnetic hysteresis of the FOPT materials
2. How many layers are needed for AMRs using the FOPT and SOPT materials with different temperature spans
3. Sensitivity of AMR to the working temperature
4. How accurate should T_{Curie} distribution be

Materials with FOPT or SOPT

La(Fe,Mn,Si)$_{13}$H$_y$ with FOPT
- Large and sharp peak in ΔS_m
- Moderate ΔT_{ad} with sharp peak
- Small hysteresis
- Tunable Curie temperature
- Relatively high thermal conductivity
- Good stability
- Multi-layer design

Gd-like material with SOPT
- Moderate ΔS_m
- Moderate ΔT_{ad}
- No hysteresis
- Tunable Curie temperature
- High thermal conductivity

Due to a rapidly decreasing isothermal entropy change ΔS_m when the working temperature is away from the Curie temperature T_{Curie}, it is expected that more layers are needed for AMRs using FOPT materials. At the same time, they may be more sensitive to the working temperature and the Curie temperature distribution.

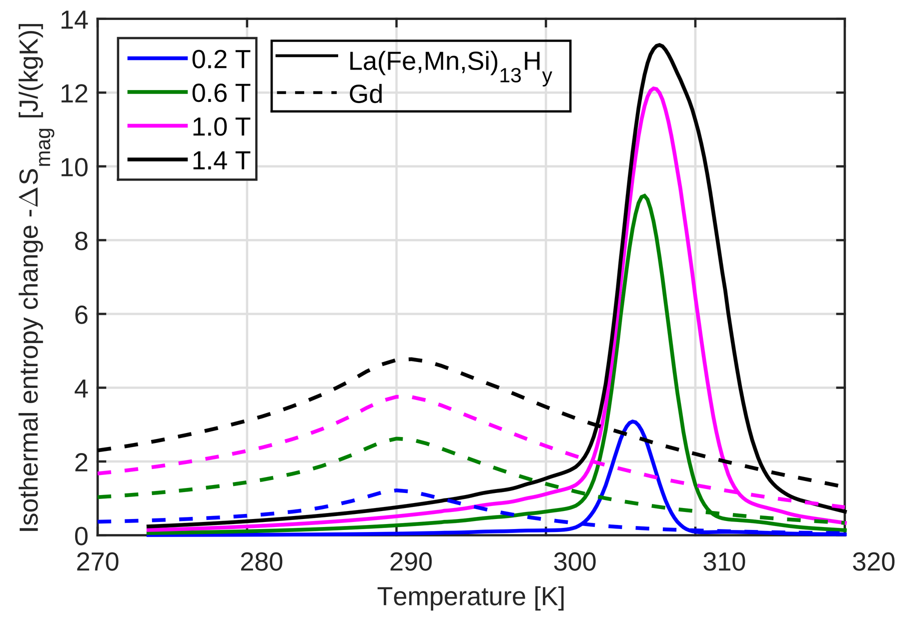

Figure 1: Isothermal entropy change of La(Fe,Mn,Si)$_{13}$H$_y$ and Gd [1,2]

Model of Active Magnetic Regenerator

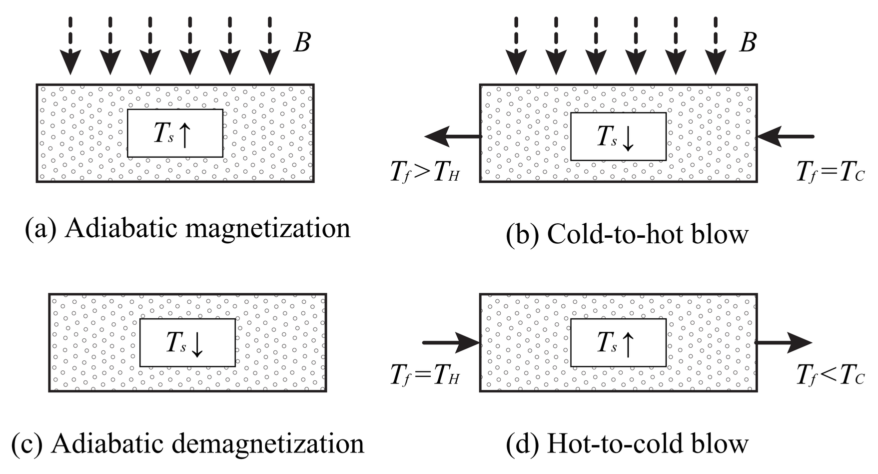

Figure 2: Active magnetic regeneration cycle

Considering the irreversibility of magnetic hysteresis, the governing equations for modeling the AMR are [2-4]:

$$A_c\frac{\partial}{\partial x}\left(k_{disp}\frac{\partial T_f}{\partial x}\right)+\frac{\mathrm{Nu}k_f}{d_h}a_sA_c(T_r-T_f)-\dot{m}c_f\frac{\partial T_f}{\partial x}+\left|\frac{\partial P}{\partial x}\frac{\dot{m}}{\rho_f}\right|=\rho_fA_c\varepsilon c_f\frac{\partial T_f}{\partial t} \quad (1)$$

$$A_c\frac{\partial}{\partial x}\left(k_{stat}\frac{\partial T_r}{\partial x}\right)+\frac{\mathrm{Nu}k_f}{d_h}a_sA_c(T_f-T_r)=\rho_rA_c(1-\varepsilon)\left[c_H\frac{\partial T_r}{\partial t}+T_r\frac{\partial s_r}{\partial H}\frac{\partial H}{\partial t}-\frac{M_{irr}}{\rho_r}\left|\frac{\partial \mu_0H}{\partial t}\right|\right] \quad (2)$$

By solving the discretized equations, the temperature gradient can be calculated after each time step given an initial condition, and the model will output the results after reaching the steady state within a numerical tolerance.

Table 1: Modeling parameters

Item	Value
B_{max}	1.4 Tesla
f	2 Hz
N_{bed}	12
D_{sphere}	0.3 mm
ε_{bed}	0.36
L_{reg}	50 mm
A_{reg}	625 mm^2
ΔT	5 - 35 K
N_{layer}	1-40
ρ_{LFMSH}	6900 kg/m^3
λ_{LFMSH}	8 W/(mK)
ρ_{Gd}	7900 kg/m^3
λ_{Gd}	11 W/(mK)

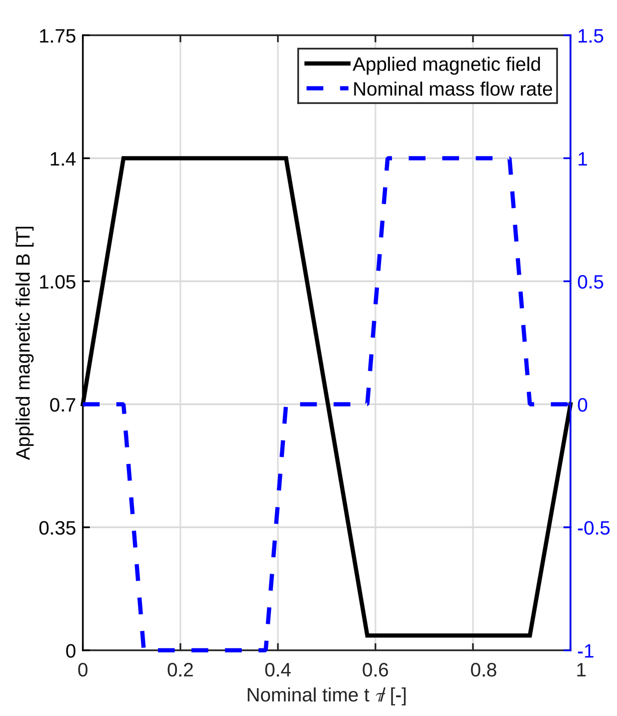

Figure 3: Applied magnetic field and nominal mass flow rate

Impact of Magnetic Hysteresis

Fig. 4 illustrates the performance of a six-layer AMR using La(Fe,Mn,Si)$_{13}$H$_y$ with and without magnetic hysteresis. The effect of the magnetic hysteresis on cycle performance becomes less significant at large mass flow rates because the hysteretic losses become small relative to the pump work.

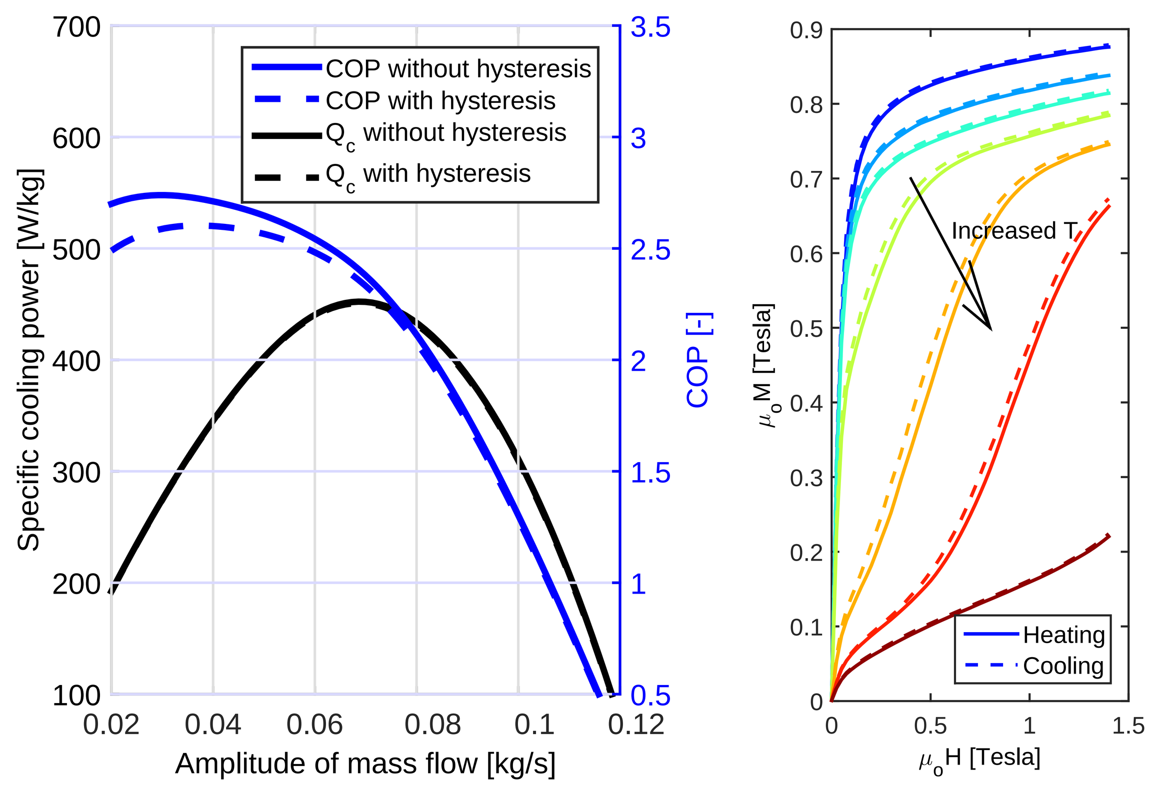

Figure 4: Performance of a six-layer La(Fe,Mn,Si)$_{13}$H$_y$ AMR with and without the magnetic hysteresis

Impact of Layer Number

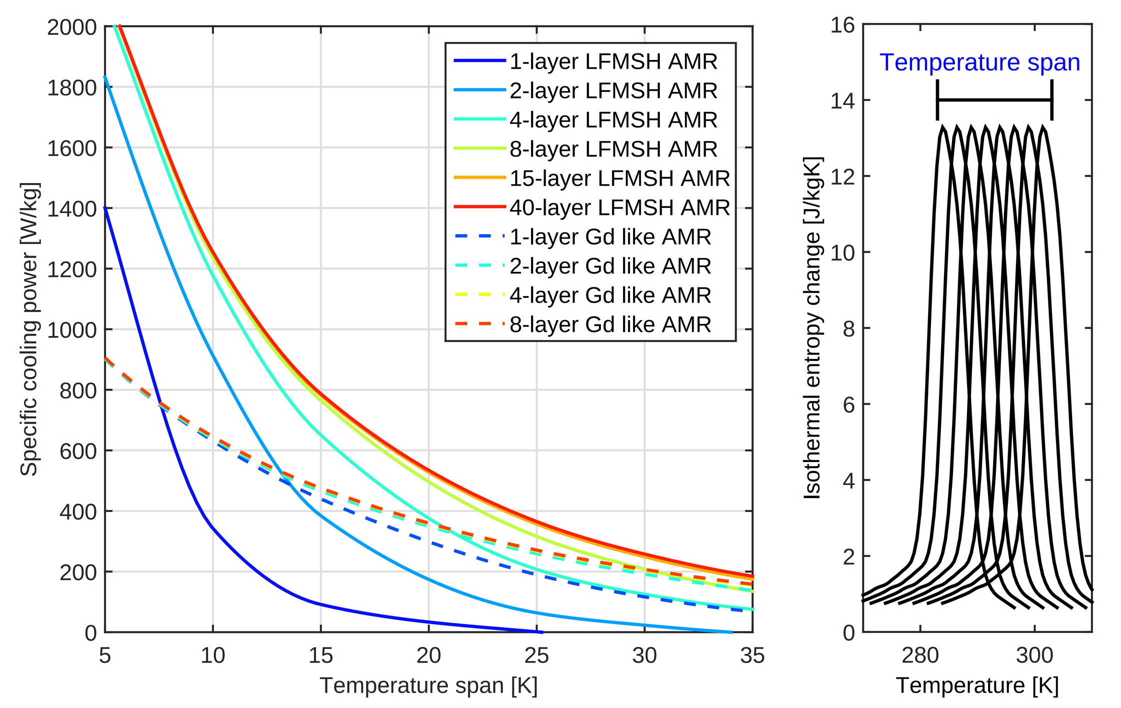

Figure 5: Specific cooling power of AMRs using materials with FOPT or SOPT

For AMRs using FOPT materials, more layers are needed to approach the theoretical maximum cooling power. However, when the temperature span is lower than 30 K it is preferable to use the FOPT materials for obtaining a higher cooling power.

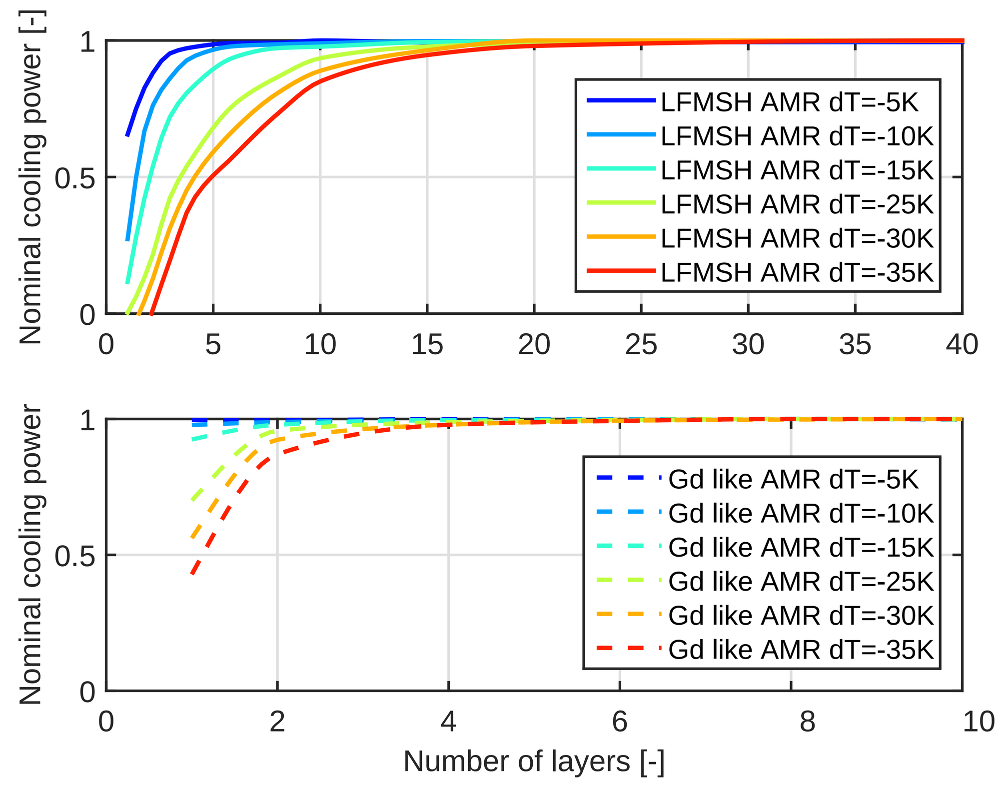

Figure 6: Nominal cooling power as a function of number of layers for AMRs using materials with FOPT or SOPT

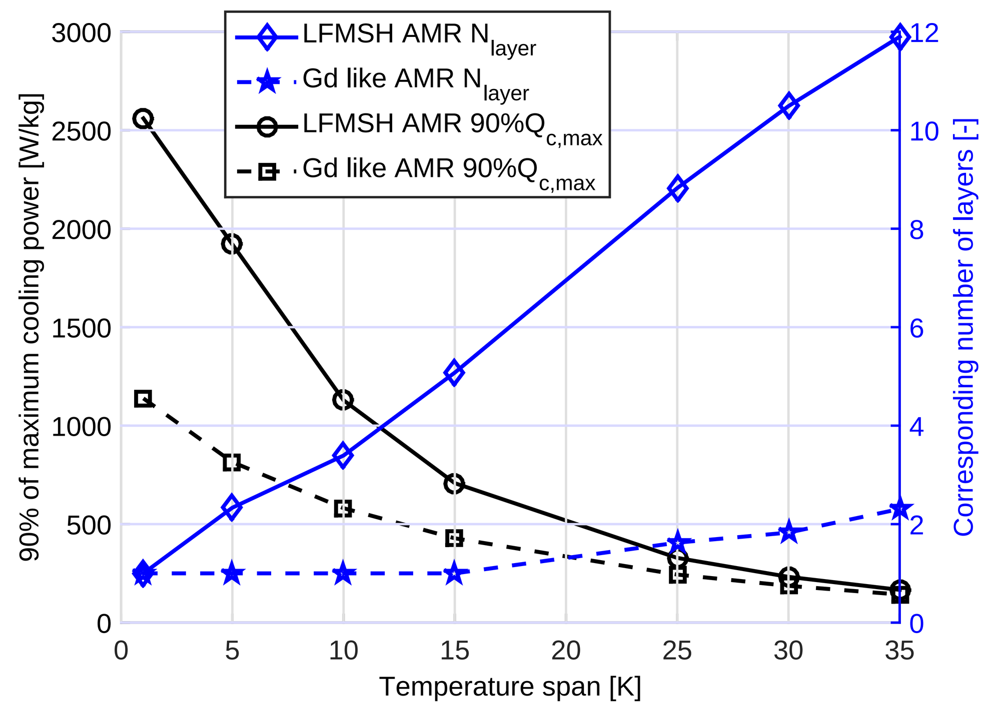

Figure 7: 90% of theoretical maximum cooling power and corresponding number of layers for AMRs using materials with FOPT or SOPT

To realize 90% of the theoretical cooling power, 3 layers / 10 K temperature span are needed for the FOPT materials, while only 1 or 2 layers are necessary for the Gd-like layered regenerator. Higher specific cooling power can be obtained with the multi-layer regenerator using the FOPT materials.

Impact of Working Temperature

AMRs using FOPT materials are more sensitive to the working temperature than the SOPT materials, although the peak cooling power is higher.

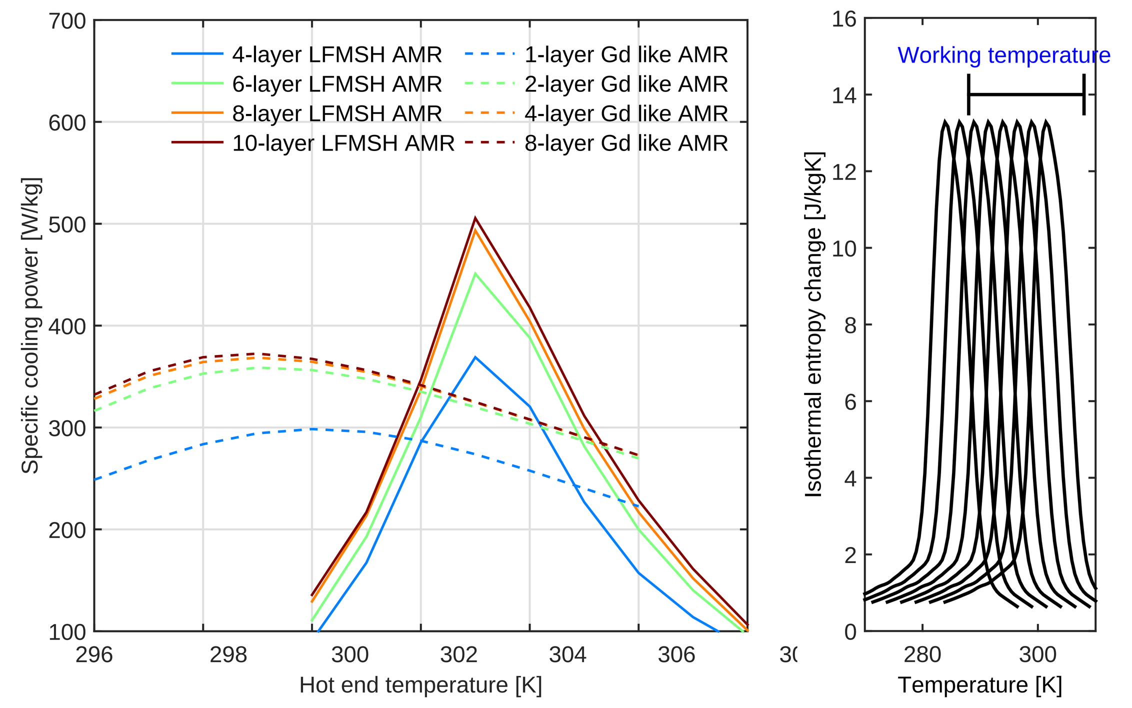

Figure 8: Impact of working temperature on the performance of the multi-layer AMRs using the FOPT and SOPT materials

Impact of Curie Temperature Distribution

There will always be some manufacturing variation in the Curie temperature T_{Curie} for the materials studied here, meaning the even T_{Curie} arrangement is difficult to achieve. This effect in the layered regenerators is quantified here.

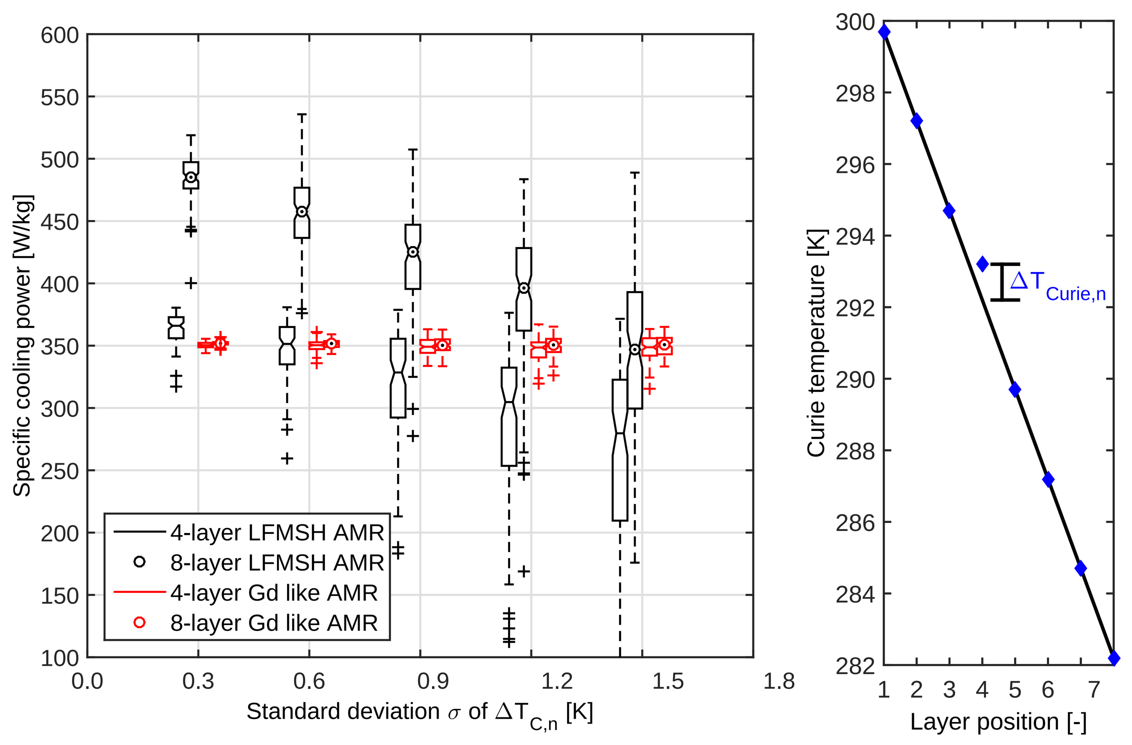

Figure 9: Impact of standard deviation σ of $\Delta T_{Curie,n}$ on specific cooling power when $\Delta T_{Curie,n}$ follows a normal distribution. For each σ, 200 AMRs with randomly generated $T_{Curie,n}$ are simulated. The central mark of the 25-75 % box is the median value of cooling power and the edges represent the 25th and 75th percentiles.

$$T_{Curie,n}=T_C+\frac{2n-1}{2n}\Delta T+\Delta T_{Curie,n} \quad (3)$$

The performance of the AMR using the FOPT materials is sensitive to the standard deviation of $\Delta T_{Curie,n}$. An 8-layer AMR is less sensitive than a 4-layer design with the FOPT materials. Although the performance of the AMR using the SOPT materials is lower, the performance can be hold even with large deviation in the Curie temperature distribution.

Conclusions

1. The effect of the magnetic hysteresis on cycle performance is significant at small mass flow rate amplitudes.
2. More layers are needed for AMRs using the FOPT materials to obtain the theoretical maximum performance. The FOPT materials are preferable for obtaining higher specific cooling power when $\Delta T < 30$ K.
3. To realize 90% of the theoretical cooling power, 3 layers / 10 K temperature span is needed for the AMR using the FOPT materials.
4. AMRs using the FOPT materials are more sensitive to the working temperature than the SOPT materials, although the peak performance is higher.
5. AMRs using the FOPT materials are sensitive to the standard deviation of the Curie temperature deviation, and using more layers could reduce the risk.

References

1. R. Bjørk, et al. J. Magn. Magn. Mater. 322(2010), 3882-3888.
2. T. Lei et al. J. Appl. Phys. 118(2015) 014903.
3. K. Engelbrecht, Ph.D. Thesis, 2008.
4. W. Brey et al. Int. J. Refrig. 47(2014) 85-97.

Acknowledgments

This work was financed by the ENOVHEAT project which is funded by Innovation Fund Denmark (contract no 12-132673). The authors would like to thank Vacuumschmelze GmbH & Co., Germany for providing the La(Fe,Mn,Si)$_{13}$H$_y$material.